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To Mr. W. R. Collard
Manager, Electrical Controls Engineering Department
Design & Development Division - Generation

SIDNEY GS & TS - GROUNDING SYSTEM TESTS

R.P. Pillai

Tests were conducted at Sidney Generating Station (GS) and Transformer Station (TS) under simulated fault conditions in order to evaluate the adequacy of the existing grounding system. Measurements have indicated that the ground potential rises and touch and step voltages at both locations for a HV station fault current of 965 A would be well under the recommended limits. Simple models were developed to validate the measurements and generalize the results. Simplified calculations have shown that the grounding system performance at the GS and TS for the above fault current with the two ground grids isolated would be under allowable limits.

1.0 INTRODUCTION

Sidney GS is an old hydraulic station with masonry walls, no security fence and with a limited amount of metallic equipment accessible to the public. Sidney TS and the GS are located close to each other, on the west and east sides of Highway 33, respectively, north of Highway 401. The 6.6 kV switchgear is located at the TS and the output of the GS is fed to the step-up transformer via 6.6 kV underground cables between the two stations. The TS is fed by four 115-kV overhead circuits namely P3S and P4S from Port Hope TS, B1S from Barrett Chute GS and Q6S from Cataraqui TS. The skywires of the HV circuits are bonded to the TS ground grid. The LV facilities at the TS include a 44-kV 3-wire system with eight overhead feeders. The grounding systems at the GS and TS are interconnected via one 107 mm^2 (4/0) copper bonding conductor installed underground and the cable shields. Eastern Region had called for a study to review the adequacy of the grounding system performance at the stations, especially with regard to public safety. As a preliminary step, soil resistivity measurements were performed by the Electrical Research Department in April, 1988 /1/ for use by the design group in calculating the grounding system performance. However, the ground grid at the GS is unknown while the ground grid at the TS may be different from that shown in design drawings. Also the ground

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grids may be connected to other underground metallic conductors such as water pipes. Furthermore, the dam and the nearby lock on the Trent Canal system may be tied to the GS grid via the railing and reinforcing bars. These uncertainties in the ground grid and its connections made design-type calculations difficult. Therefore, measurements were performed under simulated fault conditions in order to confirm the adequacy of the existing grounding system performance at the GS and TS. The project was requested and funded by the Electrical Controls Engineering Department of Design & Development Division - Generation. The tests were conducted on July 9 and 10, 1990.

2.0 TEST PROCEDURE

The 115 kV circuit P3S between Sidney TS and Dale Junction was taken out of service for test current injection and temporary working grounds (remote ground) were installed on the line approximately 10 km west of Sidney TS to sink the test current. A test current of approximately 12 A at 230 V, 67 Hz from a diesel generator installed in a van was injected between the TS ground grid and the test circuit as shown in Figure 1. All three phases of the test circuit were paralleled to carry the test current in order to reduce the circuit impedance. Figure 2 shows the layout of the station with respect to the grounding tests performed. The following measurements were then made:

a) The potential between a remotely grounded telephone pair at Sidney TS and the station ground.

b) A potential profile north-west of the TS.

c) Current splits on the skywires and metallic conductors between the TS and GS such as the bond wire, cable shields and pipes.

d) The potential between the TS and GS ground grids.

e) A potential profile along the dam and near the canal lock, with and without the lock mechanism deliberately bonded to the GS ground grid.

f) Touch and step voltages at the TS and GS.

The potentials and current splits (both magnitude and phase angle) were recorded and scaled with respect to 1.00/0 A injected current using an HP3582A spectrum analyzer in conjunction with a differential amplifier. The analyzer is capable of differentiating 67 Hz signals from 60 Hz noise. The currents were measured using clip-on current transformers with shunts. All of the instrumentation were set up in a van parked within the TS. Twisted pair cables were used to feed the test signals to the instrumentation. A spare control cable between the TS control building and GS was used to feed the voltage signals from the GS. The lock mechanism was bonded to the GS ground grid using a dedicated #10 bond wire temporarily installed for the test.

Safety precautions were observed during the tests in order to control and minimize any hazardous voltages that might appear in the event of a system fault.

3.0 MEASURED RESULTS

3.1 Measured Ground potential Rises

The measured ground potential rises (GPR) at the TS and GS are given in Table 1 along with modelled values. The potential profiles were conducted north-west of the TS as indicated in Figure 2 and along the dam at the GS. The potential profile locations along the dam are shown in Figure 3 and the corresponding measured profile voltages are given in Tables 2 and 3. The profile data at the TS are not presented here for simplicity. The profile voltages at the TS and GS were measured with reference to the respective ground grids. The dam was under extensive repair work at the time of the tests and the exposed reinforcing bars on the dam were used as remote potential probes for the profile measurement nos. 3, 4, 5 and 6. A second potential profile was conducted along the canal with the lock mechanism bonded to the GS grid. The measured profile readings were plotted against inverse distance and extrapolated to infinite distance at the origin to give the ground potential rises /2/. A differential potential of 12.7/58 mV/A was measured at the GS grid with reference to the TS grid.

TABLE 1

SIDNEY TS & GS - GROUND POTENTIAL RISES (mV/A)

	Measured	Model A	Model B
GPR at TS:			
a) From Tel. Pair	578/-6	614/0	564/0
b) From Profile	569/-3		
GPR at GS From Profile:			
a) Without Bonding	580/-7	613/0	564/0
b) With Bonding	320/-9		

TABLE 2

MEASURED PROFILE VOLTAGES ALONG DAM AND CANAL
(Without Bonding)

Test Location (Fig. 3)	Approx. Distance (m) From GS	Lock Mech.	Profile Voltage (mV/A)
1	40	-	238/-7
2	75	-	309/-8
3	95	-	380/-6
4	115	-	402/-7
5	125	-	433/-7
6	140	-	444/-7
7	-	48	458/-7
8	-	31	453/-7
9	-	28	467/-6
11	-	21	458/-7
13	-	0	458/-7
15	-	20	462/-7

TABLE 3

MEASURED PROFILE VOLTAGES ALONG CANAL
(With Bonding)

Measurement Location (Fig. 3)	Approx. Distance (m) From Lock Mech.	Profile Voltage (mV/A)
7	48	313/-9
10	24	293/-9
12	7	240/-9
14	3	192/-8

3.2 Measured Current Splits

The measured current splits for 1.00/0 A test current injection are given in Table 4 along with modelled values. The "measured" current split in the TS ground was computed by subtracting the other measured splits from the total injected current.

TABLE 4

CURRENT SPLITS (A)

Current Path	Measured	Model A	Model B
Skywires:			
- P3S	0.150/24	-	-
- P4S	0.176/12	-	-
- Q6S	0.113/24	-	-
- B1S	0.541/-3	-	-
Total	0.487/17	0.521/0	0.494/8
Conductors Between TS & GS:			
- 6.6 kV-Cable Shields	0.015/-4	-	-
- 4/0 Neutral	0.128/-17	0.135/0	-
- Control Cable Shields	0.030/23	-	-
- Metallic Pipes	0.041/19	-	-
Total (in GS Grid)	0.204/-4	0.135/0	0.204/-4
Remaining (in TS Grid)	0.356/-21	0.343/0	0.315/0

3.3 Measured Touch and Step Voltages

Touch and step voltages were measured at many locations with only the maximum results presented here for simplicity. Table 5 lists the measured touch and step voltages at the TS.

TABLE 5

MEASURED TOUCH AND STEP VOLTAGES AT SIDNEY TS

Item	Measured Voltage (mV/A)
Station Fence Touch Voltage:	
- Outside	21.9/-14
- Inside	9.16/-32
Mesh Voltage	7.42/67
Step Voltage	0.28/11
Voltage Across Main Gate	0.09/88
Between Station Fence & Grid	4.04/6
Between Station fence & SC1 Fence	6.60/-12

At the GS, a voltage of 0.80/-15 mV/A was measured between a ground rod suspended in the water near the lock mechanism (to simulate a boat) and the nearby aluminum ladder (Figure 3). With the lock mechanism bonded to the GS ground grid, the above voltage increased to 53.3/-12 mV/A. A voltage of 11.3/-7 mV/A was measured between the gate lifting hoist and the fence around the intake pond near the GS.

4.0 TOLERABLE TOUCH AND STEP VOLTAGES

The tolerable touch and step voltages for the TS were calculated as 575 V and 1857 V respectively, using equations 2.4 and 2.2 of the Grounding Guide /3/. The calculations assume a surface layer of 80 mm of crushed stone at the station and a fault clearing time of 30 cycles. The tolerable touch voltage for a person standing on a boat with bare feet was estimated as 164 V, assuming that the resistivity of the metallic boat would be negligibly small.

5.0 MODELLED RESULTS

Simple models based on an equivalent circuit were developed to calculate the ground potential rises at the TS and GS in order to validate the test results. No attempt was made to model the touch and step voltages at the stations in view of the irregular or unknown ground grid layout at the stations which greatly affects the accuracy of the calculations. Appendix A summarizes the formulas used in the calculations, other than those given in the references. Conductor earth return self and mutual impedances were calculated using simplified Carson's formulas (Appendix A).

A two-layer interpretation of the soil resistivity measurements by the Research Division in 1988 yielded a top layer of 50 Ω.m at a depth of 1 m and a bottom layer of 700 Ω.m /1/. Based on this two-layer soil model, an equivalent uniform soil resistivity of 325 Ω.m for an estimated equivalent station radius of 50 m for the TS was derived /3/ for use in calculating the station ground resistances and conductor earth return impedances.

5.1 Fault Current Shielding Factor

For a HV ground fault at the TS, the fault current entering the station grounding system is reduced by a shielding factor S (conductive component) due to the mutual coupling between the faulted phase and the skywires. For the test condition with fault current injection on the 115-kV circuit P3S, a net shielding factor of 0.968/-6 due to the skywires of P3S and the adjacent circuit P4S was calculated from the skywire self and mutual impedances. The inductive component of the fault current returning through the skywires is calculated as $(1-S)I_f$, where I_f is the total fault current.

5.2 Conductive Equivalent Circuit

Figure 4 shows the conductive equivalent circuit for the test condition with respect to the fault current source and its distribution.

An isolated station ground resistance R_g1 of 1.79/0 Ω was estimated for the TS based on the grid geometry (equation 3.1 of the Grounding Guide /3/). The ground grid layout at the GS is unknown and therefore, an isolated ground resistance R_g2 of 4.54/0 Ω at the GS was estimated based on grid conductors around and across the GS building (Model A). Alternately, the measured ground current split (Table 4) at the GS was used in the equivalent circuit (Model B).

An earth return self impedance Z_c of 0.038/74 Ω was calculated for the 107 mm^2 (4/0) copper bonding conductor between the TS and GS grids. The cable shields and the metallic pipes were neglected in Model A. Alternately, the total measured current split on the conductors interconnecting the TS and GS ground grids was used in the equivalent circuit of Model B.

A net conductive skywire impedance Z_{sk} of 1.24/11 Ω was calculated as a parallel combination of the chain impedances of the four skywires of the 115-kV circuits (1/4" steel skywire each for P3S and P4S circuits, 7 #8 alumoweld skywire for Q6S circuit and 5/16" steel skywire for B1S circuit) installed on poles, including the mutual coupling between the skywires of the P3S and P4S circuits. A pole grounding resistance of 20 Ω at every other pole was assumed in deriving the skywire chain impedances.

5.3 Modelled Current Splits and Ground Potential Rises

The equivalent circuit in Figure 4 was solved for an injected fault current of 1.00/0 A and the calculated current splits are compared with the measured results in Table 4. Note that the current split on the skywires is the sum of the conductive and inductive components. The ground potential rise is calculated as $I_g R_g$, where I_g is the ground current split and R_g is the isolated ground resistance. Table 1 compares the calculated and measured ground potential rises at the TS and GS.

5.4 Modelled Results with the Ground Grids Isolated

Eastern Region had considered separating the TS and GS ground grids in order to reduce any hazardous ground potential rise at the GS due to a HV fault at the TS. Therefore, simple calculations were performed to estimate the grounding system performance with the two grids isolated.

The calculated ground potential rise at the TS with the two ground grids isolated is approximately 714/1 mV for a HV station fault current of 1.00/0 A. The calculated skywire current and TS ground current splits are 0.602/-1 A and 0.399/1 A, respectively. Assuming a uniform soil resistivity of 325 Ω.m and point current injection, this TS ground current component would result in a voltage rise of approximately 206/1 mV/A at the GS grid. This is based on the calculated voltage profile with 100 m spacing between the two ground grids. The estimated touch voltage at the GS grid (for example at the fence) is 73.0/1 mV/A. The maximum step voltage would be close to the TS ground grid due to the earth potential profile and was estimated as 7.79/1 mV/A.

6.0 DISCUSSION OF RESULTS

6.1 Fault Level

According to a fault study by System Planning Department, the maximum (for the year 1991) fault level for a HV line-to-ground fault at Sidney TS is 5041 A. However, the fault current component of 4094 A from the grounded transformers at the TS circulates within the station without entering the station grounding system. Therefore, the net fault current (inductive and conductive) entering the station grounding system for a line-to-ground fault at the TS would be 965 A as derived from the System Planning study results.

A detailed study was not performed at this time in order to determine the worst case grounding system performance at the stations as major upgrading of the station is planned in the near future. However, the test data can be utilized for a detailed grounding study in future.

6.2 Ground Potential Rise

The ground potential rise at both the GS and TS for the above fault current of 965 A would be approximately 560 V as measured and compares reasonably with the modelled value of 590 V. Both are well below the recommended limit of 3 kV.

With a portion of the injected test current returning to the TS ground grid from the GS grid as measured, a higher GPR is expected at the TS than that at the GS. But, the slightly lower measured GPR at the TS (Table 1) may be due to mutual coupling between the potential lead and the skywires. Also, the measured voltage of 12.7/58 mV/A at the GS grid with reference to the TS grid could be mainly due to the mutual coupling between the potential lead and the current carrying conductors interconnecting the two grids. However, in view of the small difference in the GS and TS grid voltages (approximately 2% of the GPR), it was not considered necessary to correct the measured results for the mutual coupling.

Measurements indicated that the tracks and reinforcing bars in the dam were not connected to the GS ground grid. However, the dam was under extensive repair work at the time of the tests and any previous connection of the dam to the GS grid may have been temporarily removed during the construction. Therefore, the lock mechanism was temporarily bonded to the GS grid to simulate an interconnected grounding system. The increasing profile voltages with the distance from the lock mechanism as measured (Table 3) are as expected with the bonding. The ground potential rise of 320/-9 mV/A derived from the profile data with the bonding is considerably lower than the GPR of 580/-7 mV/A measured without the bonding, mainly due to the increased grid area. But, the former measured result may not be conservative as the profile readings may have been affected by mutual coupling between the potential lead and the current carrying bond wire installed along the dam for the tests. However, in view of the relatively low GPR at the station even without the bonding, it was not considered necessary at this time to estimate and apply correction factors to the measured profile readings.

6.3 Current Splits

Approximately 48.7% of the injected current returned through the skywires as measured and compares reasonably with the modelled value is 52.1%. With the poor shielding factor for the skywires, 96.8% of the injected current enters the station grounding system, as modelled.

A current split of 35.6% in the TS ground grid computed from the measured splits agrees reasonably with the modelled value of 34.3%. The measured and modelled current splits on the 107 mm^2 (4/0) neutral conductor interconnecting the two ground grids (Table 4) agree reasonably well.

6.4 Station Ground Resistances

The isolated ground grid resistance of 1.62 Ω at the TS derived from the measured GPR and current splits compares reasonably with the modelled value of 1.79 Ω. The calculated ground grid resistance of 4.54 Ω at the GS based on the assumed grid geometry is rather large compared to the value of 2.84 Ω derived from the measurements. However, calculations using the measured result indicated that the ground potential rises at the stations are reduced by only about 7%. This is mainly due to the low impedances of the interconnected TS ground grid and the skywires. The impedance of the metallic interconnections between the two ground grids was found to be negligibly small when compared to the GS grid resistance.

With the TS and GS ground grids and the skywires interconnected, the net measured shielded ground impedance of 0.580/-6 Ω at the station compares reasonably with the modelled value is 0.614/0 Ω. The interconnected ground impedance without shielding is 0.634/6 Ω as modelled.

6.5 Touch and Step Voltages

The measured mesh, step and fence touch voltages at the TS for the above fault current of 965 A were all found to be well under the tolerable touch and step voltage limits calculated for the station. The relatively small voltage (approximately 1% of the GPR) measured between the station fence and the ground grid at the TS indicates that the fence is connected to the station ground grid.

The nearly uniform profile voltages measured in the lock area (Table 2) indicate that touch and step voltages in the lock area should not be of concern with the dam isolated. With the lock mechanism bonded to the ground grid, the voltage between the ground rod installed in the water (simulating a boat) and the aluminum ladder is approximately 52 V for the above fault current of 965 A as measured and is well below the estimated tolerable touch voltage limit of 164 V. Without the bonding, this voltage was found to be negligibly small, as measured. The higher voltage measured with the bonding than that without the bonding is consistent with touch voltages in proximity to a ground grid. Here, the ground rod was installed close to the lock mechanism and was more than 20 m away from the aluminum ladder. Therefore, a 1 m touch voltage would be considerably lower than these measured voltages.

Thus, isolating the dam from the GS grid would reduce the touch and step voltages in the lock area. Such isolation can be achieved by utilizing insulated joints on all metallic connections between the GS and the dam. However, reliable isolation of the dam and lock area from the GS ground grid may not be practical. In any case, the GPR and the touch and step voltages with bonding are found to be well under the allowable limits as measured assuming present fault levels.

6.6 Isolation of the TS and GS Ground Grids

Simple calculations have indicated that the GPR at the TS would be increased from 593 V to 690 V while the GPR at the GS would be reduced from 591 V to 200 V by isolating the TS and GS ground grids, for the above HV fault current of 965 A. All are well below the recommended limit of 3 kV. Also the estimated touch and step voltages at both the stations for the above HV fault current with the ground grids isolated are well below the allowable limits.

The ground potential rises and touch and step voltages for the above fault current of 965 A with the two ground grids isolated or interconnected are all found to be well below the recommended limits. Complete isolation of the ground grids may be costly and difficult to achieve due to other unknown metallic paths such as pipes between the two stations. Furthermore, the normal grounding practice is to interconnect all ground grids in the vicinity /3/. Therefore, it is recommended that the two ground grids should be left interconnected at this time. However, the grounding system performances at both the stations should be reviewed for any future high fault levels.

7.0 CONCLUSIONS

1. With 1.00/0 A test current circulated between the Sidney TS ground grid and a remote ground using the 115-kV circuit P3S, the ground potential rises at the TS and GS were both found to be approximately 0.580/-6 V as measured. Based on this result, the ground potential rise at both the stations for a HV line-to-ground fault at the TS with a maximum (for the year 1991) fault current of 965 A entering the grounding system would be approximately 560 V and is well below the recommended limit of 3 kV. Measured results are validated by simple models.

2. The isolated ground grid resistance at the TS was found to be 1.62 Ω as computed from the measurements.

3. An isolated ground grid resistance of approximately 2.84 Ω at the GS was derived from the measurements and may be used for design calculations as the ground grid geometry at the station is unknown.

4. With the two station ground grids and the skywires interconnected, the combined grounding impedance is 0.634/6 Ω as modelled.

5. The grounding impedance of the metallic interconnections between the two ground grids was found to be negligibly small. Thus, both the TS and GS ground grids would rise to almost the same potential in the event of a HV fault, as measured and modelled.

6. The measured current split on the skywires is 48.7%. Almost 97% of the injected current enters the station grounding system due to the poor shielding of the skywires as modelled.

7. Approximately 35.6% of the injected current enters the TS ground grid as derived from the measurements. Assuming that there is no remote metallic connection to the GS ground grid, the measured current split of 20.4% may be returning through the GS ground.

8. Measurements indicated that the tracks and the reinforcing bars of the dam were not connected to the GS ground grid at the time of the tests.

9. The touch and step potentials in the lock area and at the TS for the above fault current of 965 A were all found to be well under the permissible limits.

10. Measurements indicated that the station fence at the TS is connected to the station ground grid.

11. Measurements indicated that the ground potential rise at the GS would be further reduced by interconnecting the dam and the GS grid, but the touch voltage in the lock area would be increased. However, the ground potential rises and touch and step voltages in either case were all found to be well under the allowable limits, for the above fault current. Generally it is a good practice to isolate the dam from the ground grid in order to prevent transfer of potentials to the public.

12. Simple calculations have indicated that the ground potential rises at the TS and GS for the above HV fault current of 965 A with the two ground grids isolated would be approximately 690 V and 200 V respectively. Both are well below the recommended limit of 3 kV. The estimated touch and step voltages at both the stations were also found to be under the allowable limits.

8.0 RECOMMENDATIONS

As the grounding system performance at the TS and GS with the two ground grids interconnected or isolated were all found to be well under the allowable limits for the above fault current of 965 A, it is recommended to leave the two grids interconnected at this time. However, the grounding system performances should be reviewed for any future high fault levels.

9.0 ACKNOWLEDGMENTS

We gratefully acknowledge the assistance, cooperation and contributions from District P&C, Station Maintenance and Electrical Maintenance, Eastern Region in planning and conducting the tests and the study.

Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

R.P. Pillai
Engineer
System Studies Section

RPP:am

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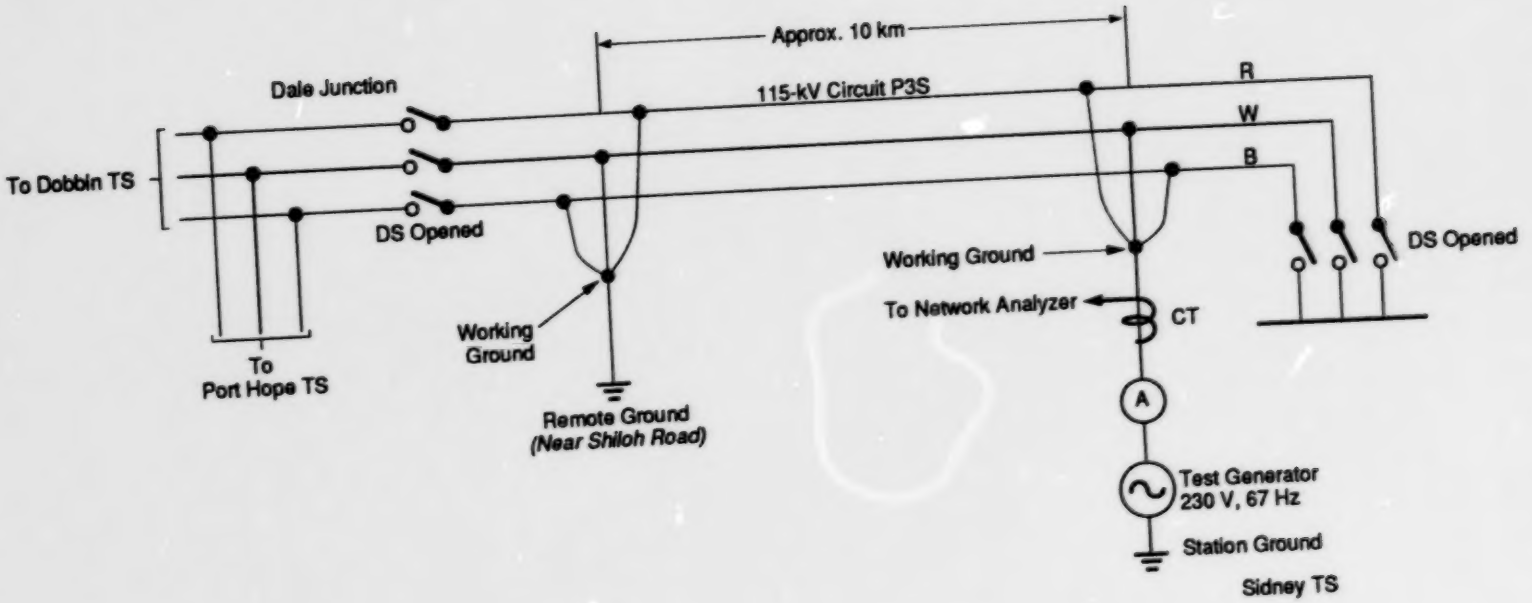

FIGURE 1

SIDNEY TS GROUNDING TESTS - CURRENT INJECTION CIRCUIT

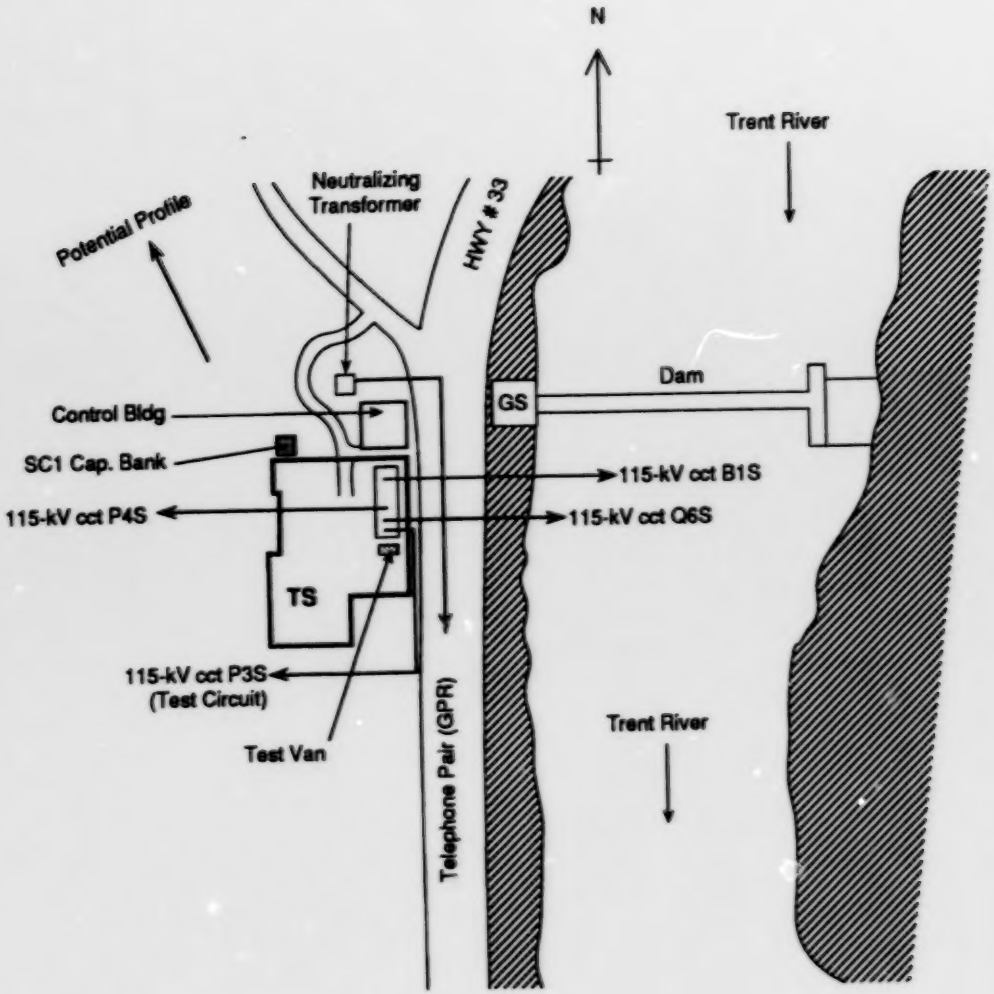

FIGURE 2

SIDNEY GS & TS - LAYOUT WITH RESPECT TO GROUNDING TESTS

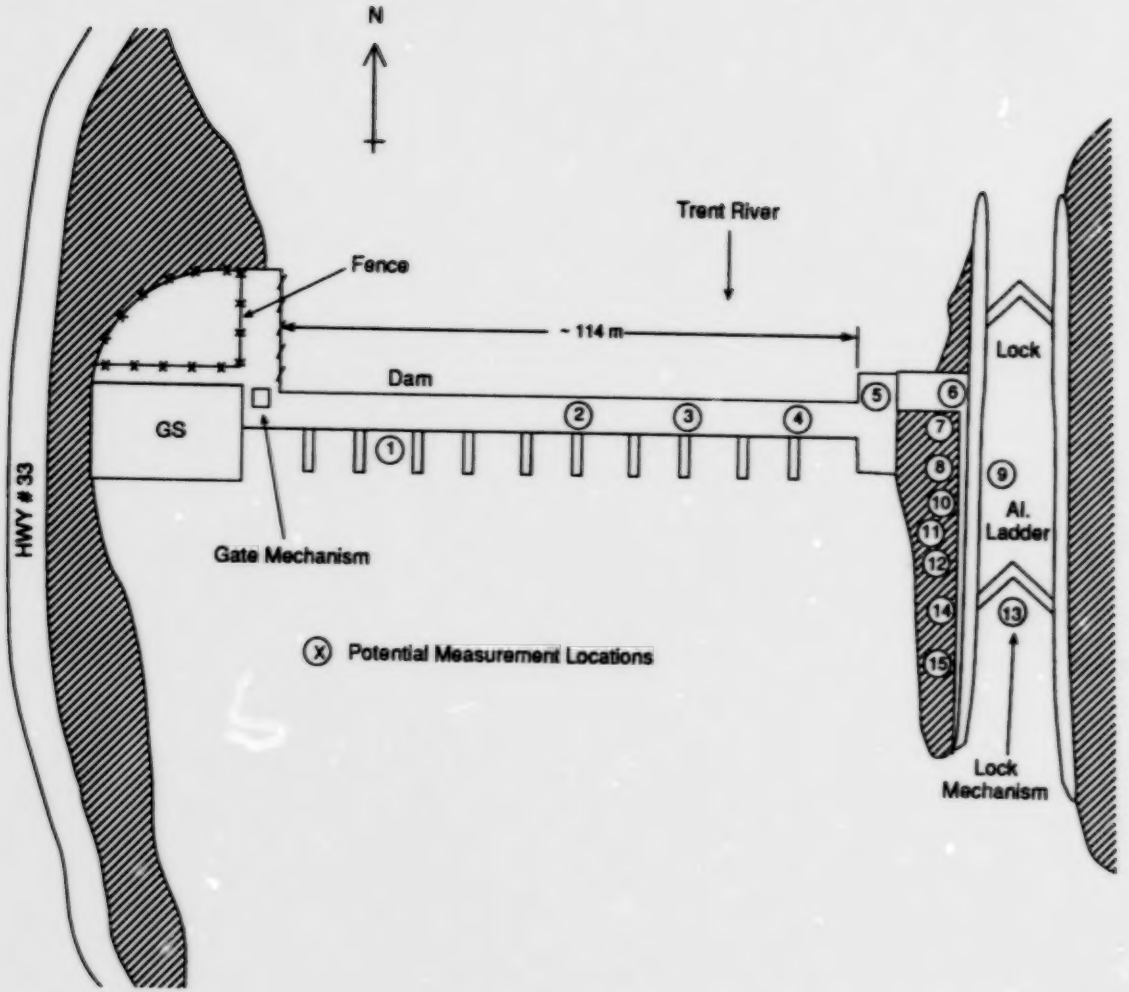

FIGURE 3

SIDNEY GS - DAM & LOCK AREA LAYOUT WITH RESPECT TO GROUNDING TESTS

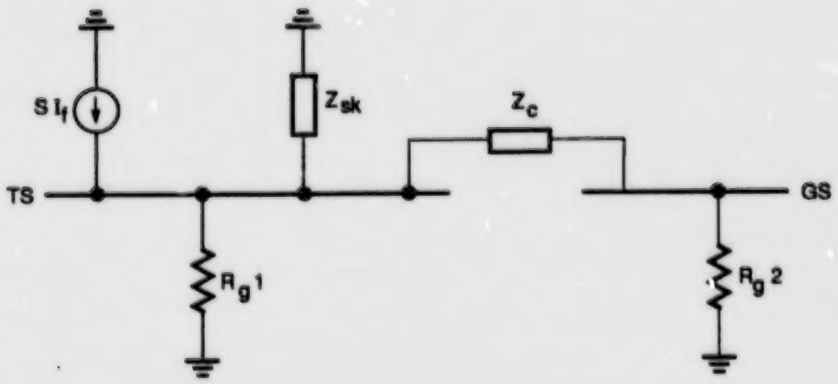

FIGURE 4

SIDNEY GS AND TS - CONDUCTIVE EQUIVALENT CIRCUIT

APPENDIX A

SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln (8440 \rho_s / GMR^2) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} (8440 \rho_s / GMD^2) \tag{5}$$

$$X_m = 0.0377 \ln [(8440 \rho_s / GMD^2) + 1] \quad (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean diastance between conductors (m)

4. Chain Impedance of Skywires, Z_{ch}

$$Z_{ch} = Z_s \, l \, R_p \quad (\Omega) \tag{7}$$

Where, Z_s = conductor earth return self impedance (Ω/km)
l = span length (km)
R_p = pole grounding resistance (Ω)

5. Shielding Factor, S

$$S = 1 - (Z_m / Z_s) \tag{8}$$

Where, Z_m = conductor earth return mutual impedance (Ω/km)
Z_s = conductor earth return self impedance (Ω/km)